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First branching fraction measurement of the suppressed decay $\Xi_c^0 \to \pi^- \Lambda_c^+$

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The Ξ_c^0 baryon is unstable and usually decays into charmless final states by the $c \to su\bar{d}$ transition. It can, however, also disintegrate into a π^- meson and a Λ_c^+ baryon via s quark decay or via $cs \to dc$ weak scattering. The interplay between the latter two processes governs the size of the branching fraction $\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+)$, first measured here to be $(0.55 \pm 0.02 \pm 0.18)\%$, where the first uncertainty is statistical and second systematic. This result is compatible with the larger of the theoretical predictions that connect models of hyperon decays using partially conserved axial currents and SU(3) symmetry with those involving the heavy-quark expansion and heavy-quark symmetry. In addition, the branching fraction of the normalization channel, $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (1.135 \pm 0.002 \pm 0.387)\%$ is measured.

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Baryons containing both an s quark and a heavy c or b quark, denoted as Q, usually decay via the disintegration of the heavy quark. There is, however, the possibility of s quark decay causing the transformation. Theoretical predictions concerning the decay widths of $\Xi_Q \to \pi\Lambda_Q$ transitions are based on the size of the s quark decay amplitude $s \to u(\bar{u}d)$ (SUUD) and the weak scattering (WS) amplitude $Qs \to dQ$ [1]. Feynman diagrams corresponding to these amplitudes are shown in Fig. 1 for Ξ_c^0 decay.

Studies of these Ξ_Q baryon decays provide a connection to theories concerning hyperon decays with those for the heavy b and c quarks. The former use partially conserved axial currents (PCAC) and SU(3) symmetry [2], whereas the latter apply more modern approaches using four-quark operators, including the heavy quark expansion, and heavy-quark symmetry (HQS). As the Ξ_b^- baryon consists of b, s, and d quarks, the WS amplitude is not present in $\Xi_b^- \to \pi^-\Lambda_b^0$ decays, so the measurement of that decay rate can be used to determine the SUUD amplitude. This information can be used to predict the Ξ_c^0 decay rate that, in principle, involves both amplitudes. Whenever a specific final state is mentioned additional use of the charge-conjugated state is implied.

The well-known Ξ_c^0 baryon consists of the c, s, and d quarks, and has a lifetime of $154.5 \pm 1.7 \pm 1.6 \pm 1.0$ fs [3]. The branching fraction $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ has not been previously measured. Several authors have made predictions using the measured SUUD amplitude and the measured lifetimes of the SU(3) triplet baryons Ξ_c^0, Λ_c^+, and Ξ_c^+, as input for determining the WS amplitude. This method was pioneered by Voloshin [1] where he used SU(3) symmetry, PCAC and the heavy-quark limit to determine an upper limit on $\Gamma(\Xi_b^- \to \pi^-\Lambda_b^0)$. In a subsequent paper, he uses the input from the LHCb measurement of $\mathcal{B}(\Xi_b^- \to \pi^-\Lambda_b^0) = (0.60 \pm 0.18)\%$ [4] and updated values for the charmed baryon lifetimes to find the SUUD rate and then calculates the WS amplitude. He predicts $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) \gtrapprox (0.25 \pm 0.15) \times 10^{-3}$ [5], assuming negative interference between the two strangeness-changing amplitudes.

Gronau and Rosner, using the same approach as Voloshin, predict two possible branching fractions for $\Xi_c^0 \to \pi^-\Lambda_c^+$ decay, depending on the sign of the interference between the two decay amplitudes [6]. Based on the measured $\mathcal{B}(\Xi_b^- \to \pi^-\Lambda_b^0)$ [4], and using charmed-baryon lifetimes available at that time, they predict $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.19 \pm 0.07)\%$ for constructive interference and $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) \lessapprox 0.01\%$ for destructive interference between the SUUD and WS contributions. We have redone their calculation using updated lifetime measurements [3,7], finding $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.14 \pm 0.07)\%$ for constructive interference and $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) \lessapprox (0.018 \pm 0.015)\%$ for destructive interference. Faller and Mannel, on the other hand, predict $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) < 0.3\%$, an upper limit obtained by assuming constructive interference [8]. Finally, Cheng *et al.* predict $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) \sim 0.0087\%$, assuming negative interference [9]. We have not updated these last predictions; the effect would be to lower Faller and Mannel's positive interference prediction and raise the Cheng *et al.* negative one, giving somewhat better agreement with Gronau and Rosner's predictions.

In this paper we measure $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ using data collected by the LHCb detector, corresponding to 3.8 fb^{-1}

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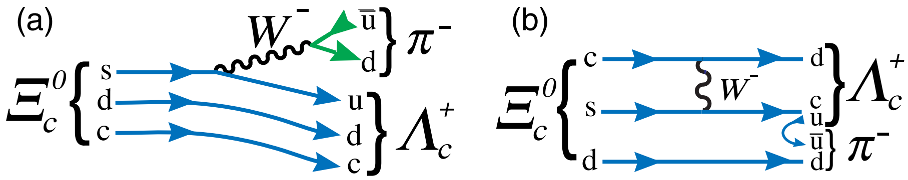

FIG. 1. Decay diagrams for $\Xi_c^0 \to \pi^-\Lambda_c^+$ transitions. (a) The SUUD amplitude, and (b) the WS amplitude.

of integrated luminosity in 13 TeV center-of-mass energy pp collisions taken in 2017 and 2018. Natural units are used in this paper with $c = \hbar = 1$. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [10,11]. The trigger [12] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which reconstructs charged particles.

Simulation is required to model the effects of the detector acceptance and selection requirements. We generate pp collisions using PYTHIA [13] with a specific LHCb configuration [14]. Decays of unstable particles are described by EVTGEN [15], where final-state radiation is generated using PHOTOS [16]. The interaction of the particles with the detector, and its response, are implemented using the GEANT4 toolkit [17] as described in Ref. [18].

In our analysis we use the prompt Ξ_c^0 sample, i.e., baryons, and their excitations, produced directly in the pp collisions. Measurement of $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ is hampered by the lack of accurately measured Ξ_c^0 branching fractions [7] to be used for normalization. A measurement of $\mathcal{B}(\Xi_c^0 \to \pi^+\Xi^-)$ with a 29% uncertainty exists [19], but the efficiency for reconstructing Ξ^- baryons is low in LHCb, in particular without a dedicated trigger line, so using this mode would lead to an unacceptably large error. We overcome this difficulty by using two indirect methods, described below, that require additional measurements of prompt Λ_c^+ and Ξ_c^+ yields, both reconstructed in the $pK^-\pi^+$ decay mode. The same decay mode is also used to reconstruct Λ_c^+ from the $\Xi_c^0 \to \pi^-\Lambda_c^+$ decays.

We use a two-step process to maximize the statistical significance of our signal channel, as well as the two normalization channels. First, we apply a set of loose selection criteria to obtain samples with large signal efficiencies and suppressed background. Subsequently, we use three different boosted decision trees (BDT) [20,21], one for each baryon decay, implemented in the TMVA toolkit [22], to further separate signal from background.

The loose selection criteria for the $pK^-\pi^+$ final states include requirements on the tracks to have sufficient transverse momenta (p_T), be separated from the primary pp collision vertex (PV), form a three-track vertex, and be identified as the hypothesized particle species. For the $\Xi_c^0 \to \pi^-\Lambda_c^+$ decay we require, in addition, that the $pK^-\pi^+$ has a mass within ± 20 MeV of the Λ_c^+ mass peak; that there is an additional π^- meson, which when combined with the Λ_c^+ candidate, has an invariant mass from -85 MeV below the known Ξ_c^0 mass [7] to 115 MeV above; and that the p_T of the Ξ_c^0 candidate is greater than 5 GeV.

The BDTs are trained with background samples from data and simulated signal samples. Background training samples for the Λ_c^+ and Ξ_c^+ candidates are taken from the sideband regions on both sides of the mass peaks. For the Λ_c^+ baryon background the intervals are 40–65 MeV away from the known Λ_c^+ mass [7]. For the Ξ_c^+ baryon training the lower and higher sidebands are taken 40–58 MeV and 40–72 MeV from the known Ξ_c^+ mass [7], respectively. The Ξ_c^0 background is constructed from like-sign $\pi^+\Lambda_c^+$ candidates within ± 5 MeV of the known Ξ_c^0 baryon mass [7]. For the Λ_c^+ and Ξ_c^+ candidates, we compute the $pK^-\pi^+$ invariant mass after constraining the three decay particles to form a common vertex and the summed momentum vector to point to the PV; this fitter is referred to as the "decay tree fitter" (DTF) [23]. In the case of the Ξ_c^0 baryon we add the additional $\pi^\mp$ meson before performing the fit. Only $1/10$ of the available $\Lambda_c^+ \to pK^-\pi^+$ data sample is used to measure the Λ_c^+ yield due to the large samples available relative to the other channels.

The variables used in the Λ_c^+ and Ξ_c^+ BDTs are the particle identification probabilities; the $\chi^2_{\rm IP}$ of the $pK^-\pi^+$ with respect to the primary vertex, where $\chi^2_{\rm IP}$ is defined as the difference in the vertex fit χ^2 with and without the p, K^-, and π^+ tracks; the angle between the particle's momentum vector and the vector from the original PV before the DTF refitting to the particle's decay vertex; the decay distance from the PV, and the DTF χ^2. The Ξ_c^0 candidates are selected by a separate BDT using the same criteria used for the Λ_c^+ by adding similar extra variables associated with the additional pion.

The BDT selections are optimized by maximizing the ratio of signal efficiency to the square root of the number of candidates in the regions where we expect signal peaks. We show the resulting mass spectra in Fig. 2; the data are fitted using the signal and background shapes described in the figure caption. The fit yields are 6320 ± 230 Ξ_c^0, 2667200 ± 3300 Λ_c^+, and 1613000 ± 3500 Ξ_c^+ signal decays. To take into account the efficiency variation we perform the fits in four bins, two in p_T and two in η, and apply efficiencies calculated in each bin.

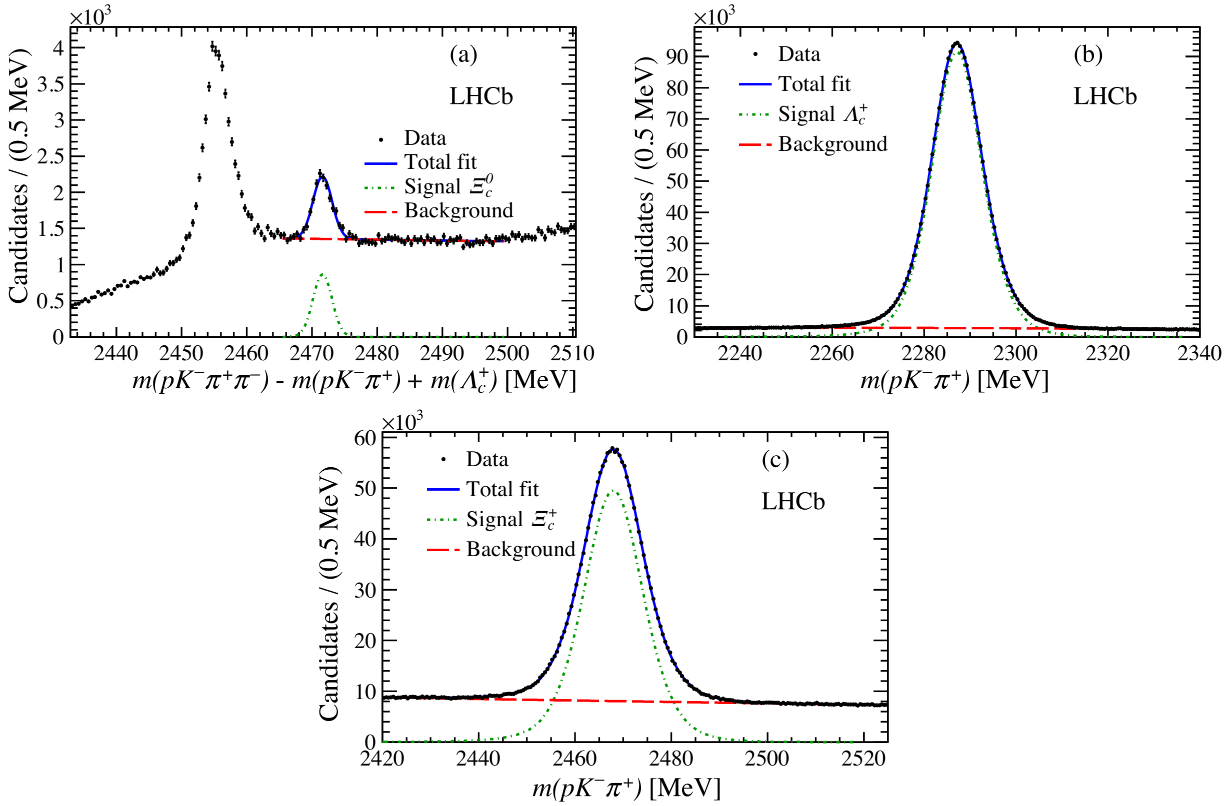

FIG. 2. Reconstructed invariant-mass distributions and signal fits of (a) $m(pK^-\pi^+\pi^-)$ showing a large Σ_c^0 signal with a smaller Ξ_c^0 signal, (b) $m(pK^-\pi^+)$ showing the Λ_c^+ signal, and (c) $m(pK^-\pi^+)$ showing the Ξ_c^+ signal. For (a) the signal shape is a Crystal Ball function [24] with a high-mass tail, and the background shape is linear. For (b) and (c) the signal shapes are double-sided Crystal Ball plus single Gaussian functions, while the background shapes are second-order polynomials. The data in (b) only use 1/10 of the available sample.

Trigger efficiencies are estimated from data, using the technique described in Ref. [25]. Selection efficiencies are determined using simulated events, which are weighted to reproduce the resonance structures in the $pK^-\pi^+$ final states visible in the Λ_c^+ and Ξ_c^+ signal samples. The overall detection efficiencies are $(0.11 \pm 0.02)\%$, $[(0.35 \pm 0.01)/10]\%$, and $(1.18 \pm 0.03)\%$ for Ξ_c^0, Λ_c^+, and Ξ_c^+ decays, respectively, where the factor of 10 is the prescale.

The first normalization method uses the LHCb measurement of the relative production fractions of the Ξ_b^- and Λ_b^0 beauty baryons, $f_{\Xi_b^-}/f_{\Lambda_b^0} = (8.2 \pm 0.7 \pm 2.6)\%$ [26]. Using HQS we equate the unmeasured production ratio of Ξ_c^0 to Λ_c^+ baryons, $f_{\Xi_c^0}/f_{\Lambda_c^+}$, to $\mathcal{C} \cdot f_{\Xi_b^-}/f_{\Lambda_b^0}$, where $\mathcal{C}$ is a correction factor for feed-downs of excited Ξ_b baryons that do not have equal rates to Ξ_b^- and Ξ_b^0 final states. This feed-down is not symmetric primarily because the $\Xi_b'(5935)^0$ state always decays to π^0 (or γ) Ξ_b^0 [27], since its mass is too low to decay into $\pi^+\Xi_b^-$. On the other hand, both the $\Xi_b'^-$ and Ξ_b^{*-} states are seen to decay into both $\pi^-\Xi_b^0$ and $\pi^0\Xi_b^-$ final states [28]. Any not yet observed higher mass states would be isospin symmetric in their decays. Accounting for all the known excited states, and the associated phase-space corrections, results in $\mathcal{C} = 1.18 \pm 0.04$, where the uncertainty arises from the errors on the relative branching fraction measurements.

The second method uses the recent Belle measurement $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$ [29]. Here we take the production of Ξ_c^0 baryons equal to that of Ξ_c^+ by isospin symmetry, e.g., $f_{\Xi_c^0}/f_{\Xi_c^+} = 1.00 \pm 0.01$ [30]. As the final state particles in the Ξ_c^+ decay are the same as in the Λ_c^+ decay, many systematic uncertainties cancel.

We determine $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ using the two measured ratios

$$\mathcal{R}_1 \equiv \frac{N(\Xi_c^0)}{N(\Lambda_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} \cdot \mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$$
$$= (0.095 \pm 0.003 \pm 0.012)\%,$$
$$\mathcal{R}_2 \equiv \frac{N(\Xi_c^0)}{N(\Xi_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)} \cdot \mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$$
$$= (5.70 \pm 0.19 \pm 0.77)\%,$$

where $N(i)$ indicates the efficiency corrected number of signal events for baryon i, f_i indicates the fraction of particle production with respect to all c- or b-quark production, and the uncertainties are statistical and systematic, respectively, a convention used in the rest of this paper. As discussed above, $f_{\Xi_c^0}/f_{\Lambda_c^+} = \mathcal{C}\cdot f_{\Xi_b^-}/f_{\Lambda_b^0} = (9.7 \pm 0.9 \pm 3.1)\%$, where we have added a 5% relative systematic uncertainty, explained later, to account for our assumption of HQS.

We also determine $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ using

$$\mathcal{R}_3 \equiv \frac{N(\Xi_c^+)}{N(\Lambda_c^+)} = \frac{f_{\Xi_c^+}}{f_{\Lambda_c^+}} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.753 \pm 0.003 \pm 0.107)\%,$$

where $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.23 \pm 0.33)\%$ [7]. The correlation matrix for these three results is

$$\begin{pmatrix} & \mathcal{R}_1 & \mathcal{R}_2 & \mathcal{R}_3 \\ \mathcal{R}_1 & 1 & 0.71 & 0.15 \\ \mathcal{R}_2 & \ldots & 1 & -0.18 \\ \mathcal{R}_3 & \ldots & \ldots & 1 \end{pmatrix}$$

The derived branching fractions are

$$\mathcal{B}_1 \equiv \mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.98 \pm 0.04 \pm 0.35)\%,$$
$$\mathcal{B}_2 \equiv \mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.41 \pm 0.01 \pm 0.21)\%,$$
$$\mathcal{B}_3 \equiv \mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (1.135 \pm 0.002 \pm 0.387)\%.$$

Their correlation matrix is

$$\begin{pmatrix} & \mathcal{B}_1 & \mathcal{B}_2 & \mathcal{B}_3 \\ \mathcal{B}_1 & 1 & 0.07 & 0.92 \\ \mathcal{B}_2 & \ldots & 1 & -0.02 \\ \mathcal{B}_3 & \ldots & \ldots & 1 \end{pmatrix}.$$

The weighted average value of $\mathcal{B}_1$ and $\mathcal{B}_2$, taking into account their correlated error, is

$$\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.55 \pm 0.02 \pm 0.18)\%.$$

Systematic uncertainties dominate these results due to our reliance on external inputs. Our assumption of HQS to relate $f_{\Xi_c^0}/f_{\Lambda_c^+}$ to $f_{\Xi_b^-}/f_{\Lambda_b^0}$ is justified by considering the analogous ratios of production fractions between charm and beauty states in 13 TeV pp collisions, $\frac{f_{D_s^+}}{f_{D^0}+f_{D^+}}$ and $\frac{f_{B_s^0}}{f_{B^0}+f_{B^+}}$. The beauty ratio is measured using semimuonic decays into a charmed meson, determined in the kinematic range $4 < p_T < 25$ GeV, and is equal to 0.122 ± 0.006 [31]. Using the total charm cross sections reported for $0 < p_T < 15$ GeV in Ref. [32], we find $\frac{f_{D_s^+}}{f_{D^0}+f_{D^+}} \approx 0.121$, where the statistical uncertainty is negligible. The systematic uncertainties in the charm-meson ratio including tracking, particle identification, luminosity, etc., mostly cancel. The uncertainties in the charm meson branching fractions cancel in the comparison with the B meson ratio, because the same values are used in both. Thus we are left with a few percent uncertainty in the comparison of the charm and beauty meson ratios. The p_T distributions of the ratios are somewhat different; they fall linearly in the beauty case [31] and are flatter in the charm case [32]. Taking this into account, a 5% relative uncertainty due to the HQS assumption appears reasonable. Contamination of the charm baryons from b-decay sources is estimated in simulation and subtracted. The resultant systematic uncertainties in the ratios are small. Table I summarizes the sources of systematic uncertainty.

In conclusion, we perform the first measurement of the branching fraction of the suppressed $\Xi_c^0 \to \pi^-\Lambda_c^+$ decays, giving $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.55 \pm 0.02 \pm 0.18)\%$. We compare with the theoretical predictions in Fig. 3; while our measurements are somewhat larger, we are in agreement with Gronau and Rosner's constructive interference prediction. Our result is also consistent with the Faller and Mannel upper limit arrived at by assuming constructive interference [8]. We

TABLE I. Systematic uncertainties in the branching fraction measurements. Ghost tracks refers to uncertainties from falsely reconstructed tracks. PID refers to particle identification efficiencies. Intermediate decays refers to the uncertainties caused by inexact modeling of the resonant structures in the charmed-baryon decays. The b-decay sources refer to charmed baryons originating from b-baryon decays included in our primarily prompt samples. Relative $\int\mathcal{L}$ refers to minor differences in the accumulated luminosities of the data samples for each of the three decays. The summed uncertainties are obtained by adding the individual components in quadrature.

	Estimate (%)		
	$\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$		$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$
Source	$\mathcal{B}_1$	$\mathcal{B}_2$	$\mathcal{B}_3$
$f_{\Xi_b^-}/f_{\Lambda_b^0}$	32	⋯	32
$f_{\Xi_c^0}/f_{\Lambda_c^+} = \mathcal{C}\cdot f_{\Xi_b^-}/f_{\Lambda_b^0}$	6	⋯	6
$f_{\Xi_c^0}/f_{\Xi_c^+} = 1$	⋯	1	1
$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$	⋯	49	⋯
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	⋯	5	5
Simulation statistics	4	3	2
Trigger efficiency	7	8	2
Ghost tracks	2	2	0
PID	1	1	1
Tracking efficiencies	2	2	0
Fit yields	6	6	3
Intermediate decays	2	2	2
b-decay sources	2	0	2
Lifetimes	3	3	2
Relative $\int\mathcal{L}$	⋯	1	1
Sum of external	33	49	33
Sum of intrinsic	12	13	6
Sum of all	35	51	34

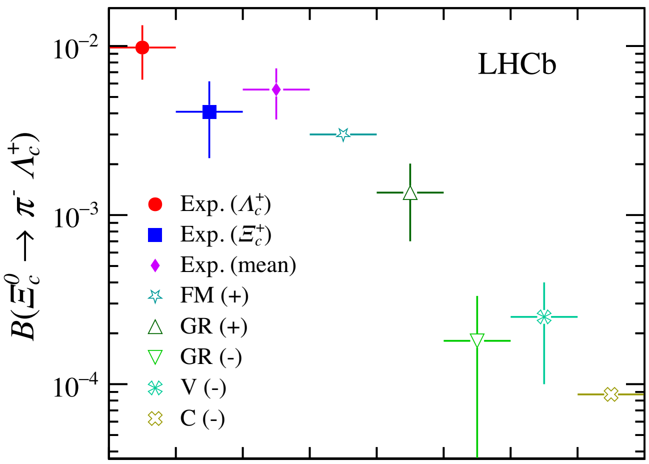

FIG. 3. Comparison of our two measurements of $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$, and their average, with the lower limit of Voloshin (V) [5], the upper limit of Faller and Mannel [8] (FM), updated predictions of Gronau and Rosner [6] (GR), and Cheng *et al.* [9] (C). The (+ or −) indicates if positive or negative interference between the SUUD and WS amplitudes is assumed.

disagree, however, with Cheng's prediction of $\mathcal{B}(\Xi_c^0 \to \pi^-\Lambda_c^+)$ assuming negative interference [9]. In addition, the branching fraction of the normalization channel is found to be $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (1.135 \pm 0.002 \pm 0.387)\%$, that is somewhat larger than, but in agreement with a previous Belle measurement [29], and has a better relative precision.

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